Impact of climate change on mountain environment dynamics

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An introduction

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An introduction

1 Mountains are specific ecosystems, characterised by their diversity and complexity (Messerli and Ives, 1997). Steep topographic, climatic and biological gradients combined with sharp seasonal contrasts favour the triggering of extreme climatic and geomorphic events, which may in turn strongly affect ecological and human environments (Ives and Messerli, 1989; Price, 1999; Beniston, 2002; Viviroli *et al.*, 2007; Hüggel *et al.*, 2010; Körner, 2013). Mountain populations are quite diverse in their way of life: traditional rural activities, such as agriculture, livestock grazing and forestry, coexist with mining extraction, hydropower production and tourism (Beniston *et al.*, 1996). Depending on the socio-economic and demographic context of each country, such activities are nowadays either declining or in full expansion. In fact, while 12 percent of the world's population live in mountains, the great majority live in marginalised (physically and economically) developing countries so that any change in environmental conditions may have an impact on poverty and food security (Kohler *et al.*, 2014). Mountains also play an important role in their adjacent lowlands: they are "water towers" (Liniger *et al.*, 1998; Viviroli *et al.*, 2007) storing and delivering fresh water to downstream areas, and producing energy through hydropower potential (de Jong *et al.*, 2009; Viviroli *et al.*, 2011; Beniston and Stoffel, 2013). However, mountain environments are "fragile", they can be damaged by many factors such as deforestation, overgrazing by livestock, cultivation on marginal soils, and progression of urbanisation, all of which may result in (1) a rapid degradation of biodiversity and water resources, and (2) an increase in natural hazards, hence putting adjacent populations at risk.

2 Mountain environments are very sensitive to climate change (Beniston, 2003, 2005). They appear among the most severely and rapidly impacted ecosystems, and can be affected by any change in temperature and precipitation patterns at all scales (Zemp *et al.*, 2009). Snow and ice are the main control parameters of the hydrological cycle, particularly of the seasonal runoff, and may impact the entire geosystem (rocks, soils, vegetation, and river discharges). With climate change, water will probably become less available, the consequences of which will reach far beyond mountain regions (Lutz and Immerzeel, 2013). Similarly, climate change is likely to increase exposure to either natural or economic hazards, all the more so because in many mountain areas, poverty levels are higher than in lowland areas and food insufficiency is more widespread (Ives and Messerli, 1989; Kohler *et al.*, 2014).

3 However, assessing the potential impacts of environmental changes is not easy because of the complexity and diversity of mountain systems, and because of the natural intra- and inter-annual variability of the climatic parameters, which make the exact nature of climate change very difficult to evidence (Immerzeel *et al.*, 2010; Salzmann *et al.*, 2014). In fact, predicting future climate trends relies on both a large network of meteorological stations and modelling outputs from satellite-derived data (Beniston, 2003; Immerzeel *et al.*, 2009; Nolin, 2010). Yet, trends can currently be generated only on a decadal time scale.

4 This issue is devoted to the "Impact of climate change on mountain environment dynamics", and focuses on the evidence for climate change at local and regional scales. It aims to provide some answers to the following questions:

1. What are the different methods to assess changes in climate? Which are the best, most accessible and integrative ones?
2. What are the best field indicators of climate change? How can the impacts caused by climate change, in the strict sense, be differentiated from those linked to land use change?

3. Do mountain populations perceive any evidence of climate change (temperature, precipitation amount, seasonality and extreme events) at a local scale? Do they feel threatened?
4. How do policymakers reconcile socio-economic assets (ski resorts, water supply, etc.) with climate change data and trends?

5 This issue includes seven contributions, which encompass a wide variety of methodological approaches and themes applied to different mountain systems situated in four continents, with a special place given to the French Alps.

6 The first contribution by Einhorn *et al.* is an overview of the results achieved during the period 2007-2013 in research, cooperation and capitalisation projects on climate change. It is mainly a survey of the observed and projected changes in climate patterns, cryosphere dynamics, and derived and expected natural hazards (floods, debris flows, landslides, and rockfalls). These authors review existing databases on climate change and natural hazards at different levels (i.e. international, European and French), highlighting the platforms and observatories developed by different scientific and technical operators at the European Alps scale. Some significant socio-economic impacts are also mentioned, in relation to potential extreme hazards, in order to urge stakeholders and policymakers to anticipate and adapt to these new, foreseeable situations.

7 The two following contributions deal with permafrost (i.e. permanent ground ice). At high elevations, one good indicator of climate change is permafrost, a major element of the mountain cryosphere whose existence is generally best demonstrated by hanging glaciers or rock-glaciers. Any change in permafrost conditions (temperature or extent) may generate new risks for the surrounding mountain population, infrastructures and territories (Haeberli and Beniston, 1998; Huggel *et al.*, 2010; Haeberli, 2013).

8 In their study, Bodin *et al.* provide a synthesis of the current status of mountain permafrost in the French Alps and its recent evolution. They summarise research that has been carried out for the last ten years within the framework of PermaFRANCE, a network that was set up to monitor the long-term evolution of permafrost. Temperature measurements include both surface (sensor) and subsurface (borehole) methods. The preliminary results obtained for the last 5 five years show a clear tendency of increasing temperatures, which is consistent with data collected from other Alpine boreholes. They then illustrate the hazardous geomorphological processes observed as a response to permafrost changes: increasing rockfall activity in the Mont-Blanc massif, increasing velocity of rock-glaciers such as the Bérard in the Vanoise massif, with extreme dynamics correlated with meteorological anomalies and hydro-snow conditions. In their conclusion, the authors emphasise the conditions of stability of alpine slopes, which are clearly modified by the warming of permafrost and related changes in the ice or water contents of soils. Therefore, understanding and predicting the consequences in terms of risks should take into account the very high variability of the local conditions in order to meet societal expectations, specifically those of natural hazard managers.

9 This recommendation is taken seriously by Duvillard *et al.* who focus on the risk of the direct destabilisation of high-mountain infrastructures (huts, cable-cars, etc.) generated by global warming. In order to characterise the potential hazards and assess the vulnerability of such infrastructures probably threatened by permafrost degradation and/or possibly affected by glacier shrinkage, the authors have carried out an extensive inventory of all high-mountain infrastructures (n=1,769) in the French Alps. For each one, they consider a series of factors characterising the geomorphic hazards (either passive or active) that may cause slope instability. They also include the potential level of damage intensity, together with an index of value (both financial and operating) in order to assess the degree of vulnerability better. Finally, they build an index of destabilisation risk to identify and rank infrastructures at risk. On the basis of all these parameters, they conclude that 10% of the studied infrastructures are characterised by a high risk of destabilisation, a warning that should be seriously taken into account by stakeholders and policymakers.

10 Besides slope destabilisation and the threat to infrastructures due to temperature increase, climate change in mountains has significant impacts on hydrology, which may threaten

populations living in the mountain areas and in adjacent, lowland regions. Mountains provide water resources for domestic, agricultural, industrial and tourism purposes, and any change in this resource (either surface or groundwater) may affect water availability and hence any economic activity based on this resource. This is all the more true as mountain areas now host larger population densities. Four contributions illustrate the varying water uses in different socio-economic contexts and continents.

11 Water availability is a crucial issue in mountains where agriculture remains the major source of economic income. In the Anti-Atlas mountains of Morocco, Aziz and Sadok show how saffron production, a major pillar of the local economy, is a fairly water-demanding crop and as such is directly threatened by climate variability. More specifically, it appears that the general temperature rise of recent decades has shortened the cold season, and the decrease in snow volume in the mountains has led to a water deficit, and hence a reduction in the economic profit generated by this emblematic cash crop. In order to assess better the local perceptions of climate change, the authors surveyed 60 farmers (using questionnaires), and a few stakeholders (semi-structured interviews). They show how, in order to minimise the loss of profit generated by climate change, the local population has developed adaptation strategies, integrating imported "technical" knowledge (e.g. drip irrigation; changes in the planting and irrigation calendar) with traditional knowledge inherited from past generations (renovating old wells or digging new ones).

12 The position of the Argentine Andes on the rain-shadow side of the mountain range makes them even more sensitive to climate change. In this arid region (150-300 mm mean annual precipitation) studied by Delbart *et al.*, the annual snowmelt is the main source of running water and aquifer recharge, which directly supply the irrigated agriculture of the piedmont oases in Mendoza Province. There, the growing population and increasing water demand make access to the water resource a priority, which requires some anticipation. The authors analyse the link between the seasonal and inter-annual variations in river discharges measured upstream of the first dams built on the four rivers feeding the irrigated plots. In order to forecast the average river discharge during the spring–summer months, they use a remote sensing methodology based on MODI10A2 images (2001-2014 period). Despite the period of analysis being too short to conclude there is a significant regime change, the authors show that large differences in discharge are related to the total surface area of the snow cover among watersheds, with a direct link to watershed dimensions. They also show that the area of the snow bed extent observed at the beginning of the snowmelt period directly influences the total discharge in rivers. Finally, their method proves effective at forecasting over 60% of the inter-annual variation in discharge, and could help to manage water levels in reservoirs located upstream of the irrigated perimeters.

13 Smadja *et al.* focus on the Himalayas, and more specifically the Koshi basin (Nepal) dominated by Everest. In contrast with the many studies based on climate modelling, the authors' aim was to find out whether populations had noticed any variations in water availability that affected their usual agricultural practices and whether they attributed them to climate change. In a very original approach, i.e. "studying climate change without speaking about it", the authors try to distinguish the real impacts of climate change from those of an increasing water demand due to the spread of new techniques in agricultural practices, new lifestyles and the development of tourism (10 times greater than in 1980). From extensive interviews carried in four fieldwork sites representative of Nepalese milieus, they find contrasting situations and changes in practices with no obvious connection to the climate. Nevertheless, their information collected about snow, a parameter that has been measured incorrectly and underestimated in simulations, shows that populations are more affected by fluctuations in rainfall patterns than by the melting of glaciers and the snow cover. The authors conclude that the population groups most likely to be affected by climatic variations are those living in high mountains and low mountains (where the long dry season is quite often problematic), compared to those living in the middle mountains and the foothills where their pluri-activity (agriculture, portage and services) limits the risk that might be caused by irregular, insufficient rainfall. More

generally, the recent demographic growth, infrastructure development and diversified incomes have appeared as alternative explanations of the changes observed other than the climate.

14 The last contribution addresses the issue of water availability for artificial snowmaking, a common practice in the European Alps for the last fifty years (Koenig and Abegg, 1997; de Jong, 2011). Snowmaking is considered a logical way to extend ski resorts spatially, to compensate for the seasonal deficit in snow and mitigate the effects of climate change. This guarantee of snow represents extra investments that may not be financially viable for all ski resorts in the future.

15 By looking at the climatic context, Spandre *et al.* try to assess the current and anticipated levels of snowmaking facilities at the scale of the French Alps. They set up a socio-economic on-line survey for professionals, including ski patrol managers and technicians working in ski resorts, in order to classify the ski resorts according to their size, elevation and equipment (number, age and size of ski lifts). They establish a ratio of equipped surface area that turns out to be larger for large resorts than for small and medium-sized resorts. Then, they assess the past evolution of the meteorological conditions suitable for snowmaking (wet-bulb temperature between -2°C and -5°C), and find that the snowmaking potential for the Alpine stations surveyed decreased overall from 1961 to 2014, with some seasonal and annual variability. Therefore, the scarcity of water availability and weather conditions favourable for artificial snowmaking is likely to become an increasingly common situation, representing an increase in costs for ski resorts that only the richest (largest and highest) will be able to bear.

16 To conclude, the different contributions of this volume show that, although the issue of climate change is being taken more seriously worldwide (see the next COP 21 conference to be held in Paris in December 2015), its expression is far more complex at a local level, and its perception varies depending on the expected impacts. In mountainous areas, two parameters are particularly significant. Firstly, and in addition to glaciers and their accelerated retreat, ground-ice status appears a good indicator of temperature rise and hence a possible cause of slope instability when ground-ice progressively melts, putting tourism infrastructures at risk. Secondly, the water resource has become the main concern for populations living in the mountains or their foothills. The melting glaciers, and more importantly the decrease in snow volume and duration, and its temporal and spatial variability, will affect the discharges of springs and rivers, and hence the availability of water for mountain people. In addition, change and variability in rainfall, two parameters not well constrained by global and regional climate models, are certainly key factors that must be better defined at catchment and local scales. Depending on the uses of water, its scarcity will affect local economies (reduction in cash crop production; bankruptcy of smaller ski resorts if snowmaking is no longer possible), and/or may create some competition between different socio-economic activities (tourism vs. agriculture), and some conflicts between populations who can adapt either financially or by diversifying their economic activities (stakeholders, rich landowners) and those who have no option but to move or perish, despite their experience of climate variability gained over generations. Finally, even if some impacts, such as hydro-geomorphic hazards and biodiversity evolution, have not been expressly documented in this volume, we hope that through the different examples developed, some methodological approaches (remote sensing, destabilisation risk index, interviews on perceptions) might be useful to define the appropriate policies required in order to anticipate, adapt to, and manage the potential impacts of climate change in mountains.

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